Fabrication, alignment, and integration of glass mirrors

Will Zhang

X-ray Astrophysics Laboratory

NASA Goddard Space Flight Center

Acknowledgements

GSFC:

Kai-Wing Chan
David Content
John Lehan
Rob Petre
Timo Saha
Will Zhang

MSFC:

Bill Jones
Mikhail Gubarev
Steve O'Dell

SAO:

Paul Reid

Technology Development Manager:

Scott Owens

Laboratory Manager:

Curtis Odell

Technical Support:

James Mazzarella Marton Sharpe
Melinda Hong Theo Hadjimichael

This work has been supported in part by

The Constellation-X Project Office
GSFC Core Competence Fund
A NASA Astronomy and Physics Analysis Grant
GSFC Internal R&D Fund
GSFC Technical Equipment Fund
GSFC Director's Discretionary Fund

Four Questions and Answers

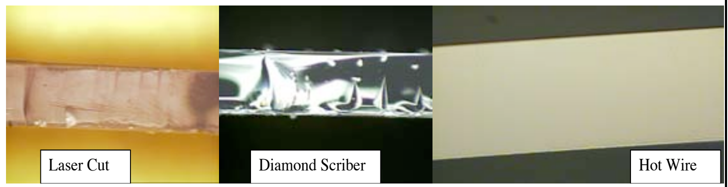
(for a given set of requirements: mass, angular resolution, schedule, and budget)

- Can we make the mirror segments?
  - Developed a precision glass forming technology
  - Invented a glass cutting technique that leaves fracture-free edges
- Can we measure them, overcoming gravity and handling distortions?
  - Using Fizeau phase-measuring interferometers
  - Designed and fabricated a cylindrical null lens system
  - Invented a mirror support (aka a mattress) to reduce/cancel gravity distortion
- Can we align and integrate many (hundreds to thousands) of them into mirror assemblies?
  - Implementing a “Fabricate and Assemble” approach
- Can these assemblies survive the launch and space environment: acoustical, vibrational, and thermal
  - A mechanical mock-up structure is being made, will be tested in acoustic and vibration chambers

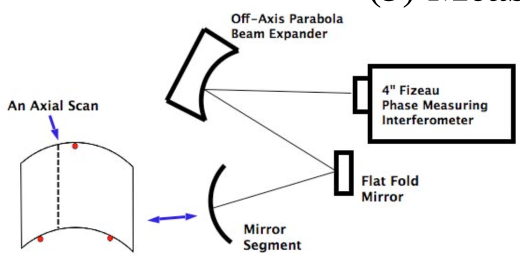
Mirror Fabrication and Metrology Process

(1) Slumping

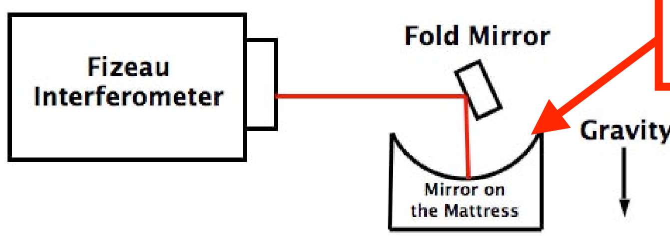
(2) Trimming



(3) Measuring

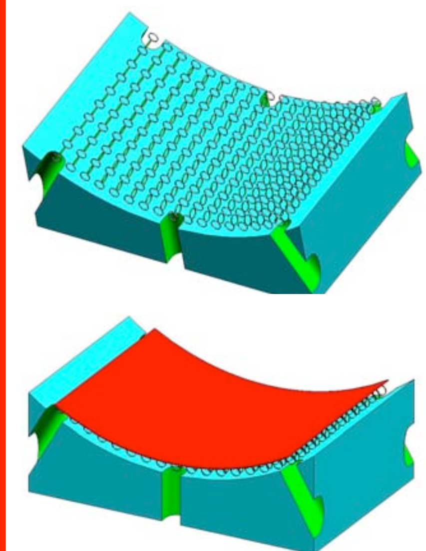


Current Setup

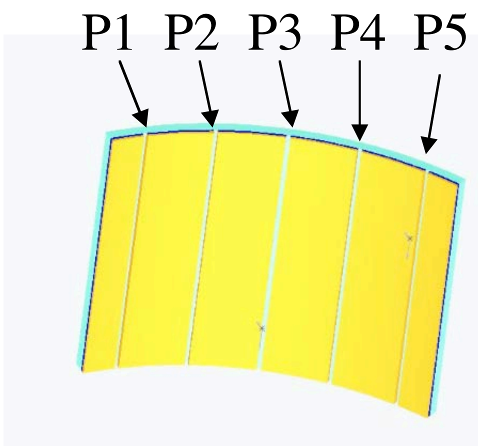


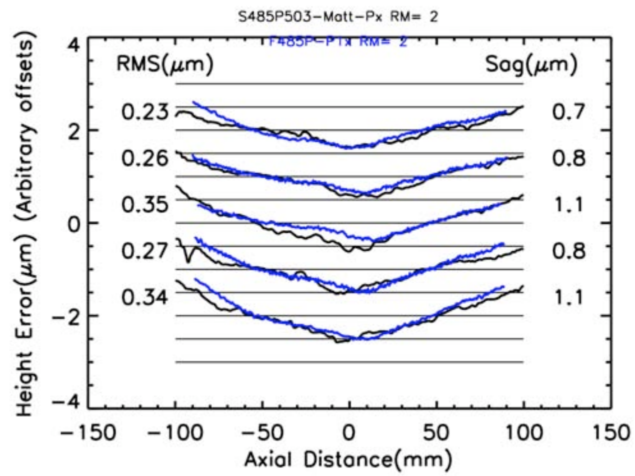
New Setup, being implemented

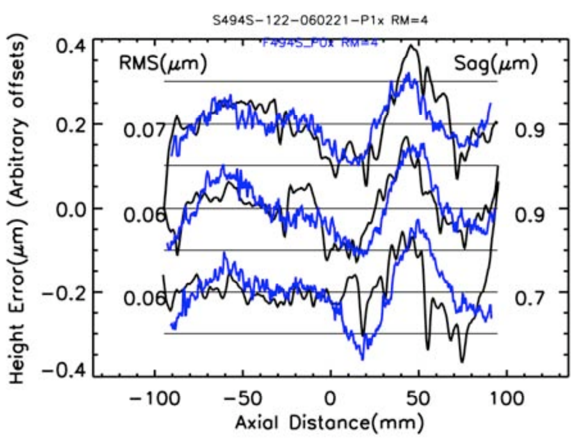
Mirror Support

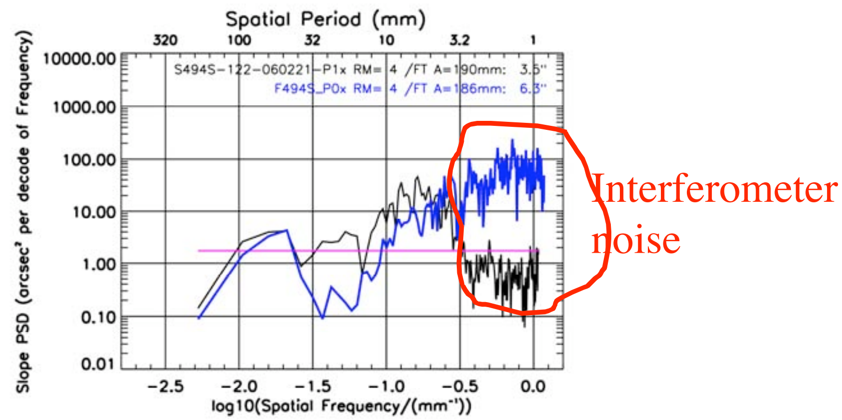


Typical Mirror Quality



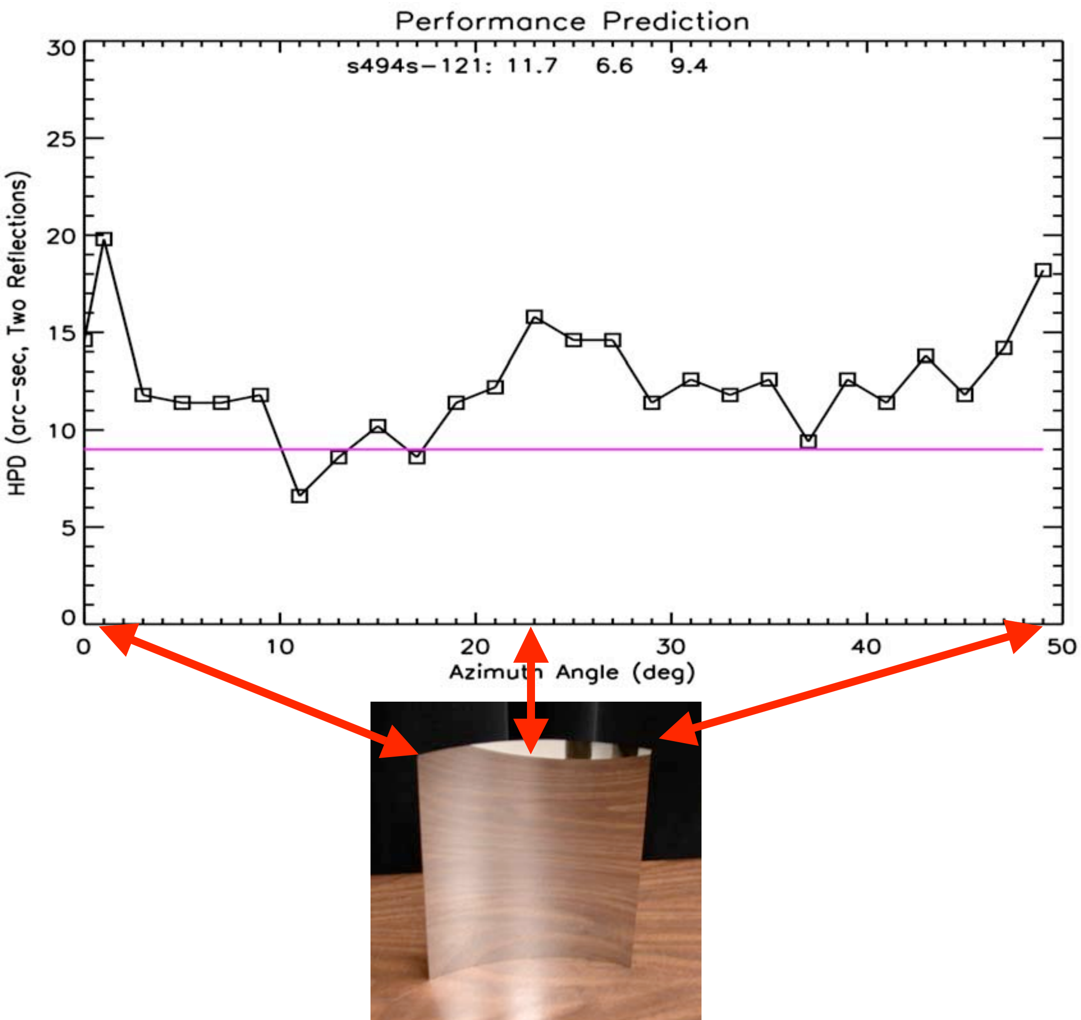






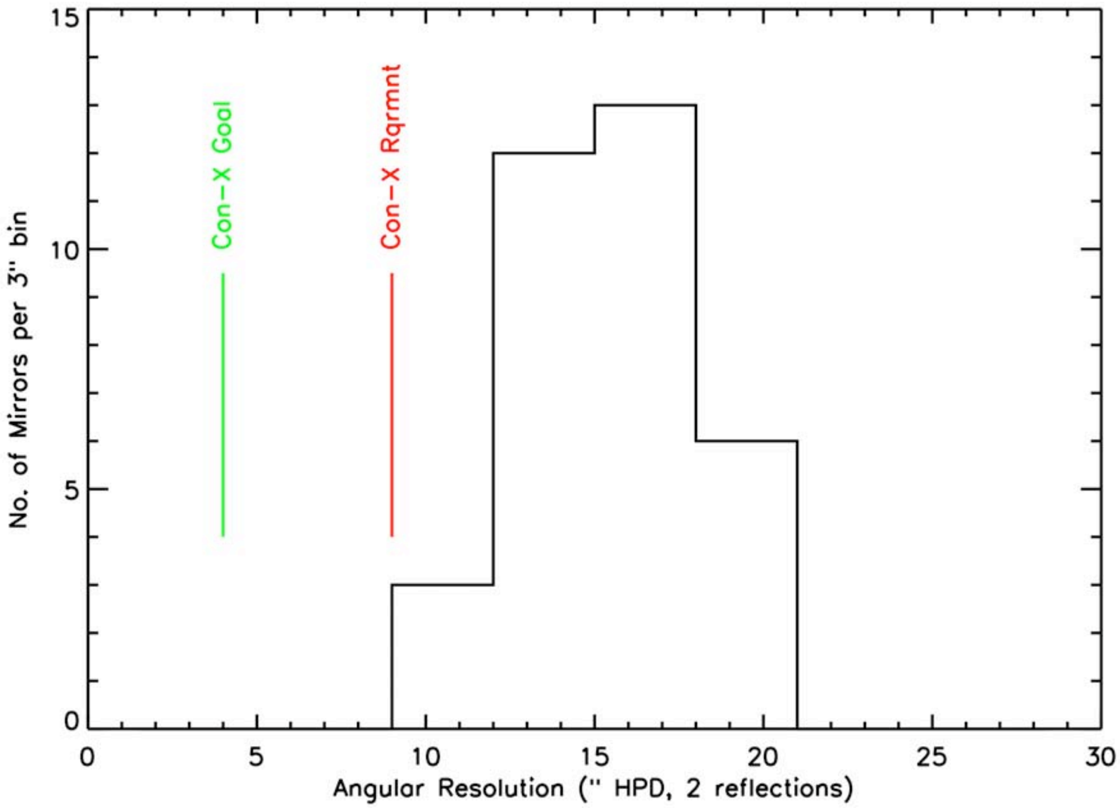
Apparent Performance of a Typical Mirror Segment

(including both mirror intrinsic error and gravity distortion)



Distribution of Apparent Mirror Quality

(all mirrors produced between Jan and Apr 2006)



Error Decomposition

Overall Axial Figure	14.9		
	Mandrel	6.0	
	Metrology	10.0	
		Reference Optics	7.0
		Gravity Distortion	7.0
	Forming	9.2	
		Low Order Figure	2.0
		Mid-Frequency Figure	8.5
		Random Error	<3

Easy to solve (Reference Optics, 7.0)

Relatively easy (Gravity Distortion, 7.0)

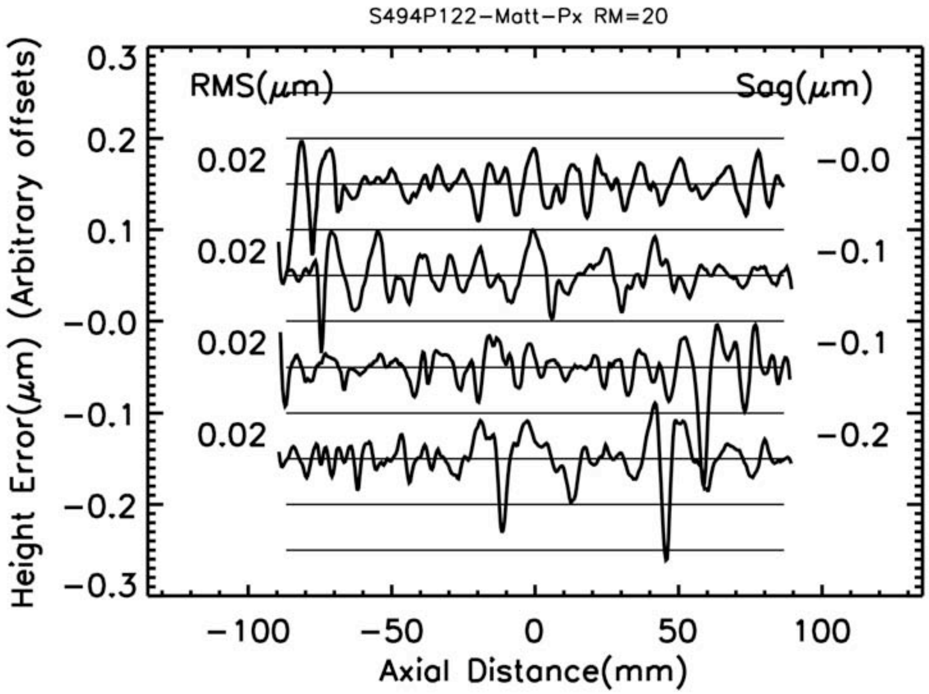
No. 1 Issue (Mid-Frequency Figure, 8.5)

Potential of this technology (Random Error, <3)

Features of Glass Forming

- It is a totally deterministic process, having very little random error
- It preserves the glass sheet's thickness
- It preserves the glass surface micro-roughness
- It is an isotropic process, namely the surface error is the same in the axial direction and the circumferential direction
- It duplicates the low order figure of the forming mandrel with a very high degree of fidelity: spatial scale > 20 mm
- ***But it introduces additional mid-frequency errors: spatial scale between 2 and 20 mm; These errors currently dominate the mirror X-ray performance***

Meet the mid-frequency error face-to-face



Features: very small amplitudes (P-V less than 100nm) but fairly large slopes because of short spatial periods

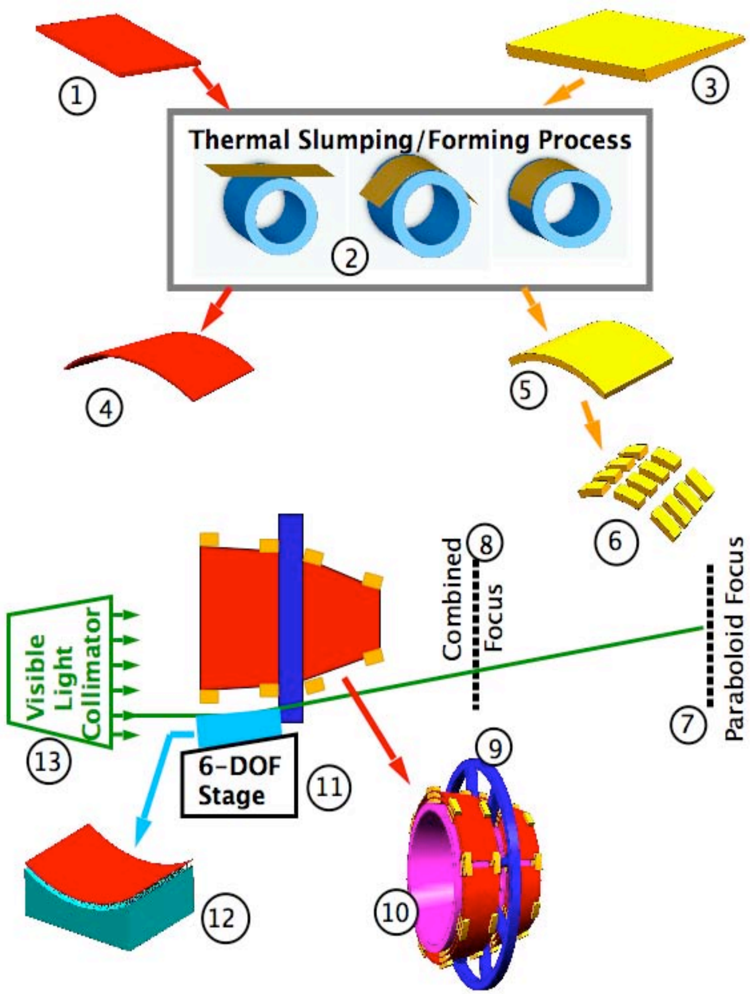
Cause, reduction and/or elimination of the mid-frequency errors?

- **Cause:**
  - Dust: particles in the ambience trapped/sandwiched between the glass sheet and the forming mandrel surface
  - Detritus: particles shed by the release layer
- **Reduction/Elimination**
  - Improving the environment and the release layer
  - Epoxy replication
  - Light polishing/buffing

Existing/Proposed Mirror Alignment/Integration Methods

- Electric-Discharge machined (Wire-EDM) aluminum combs (Serlemistsos et al. 1989): BBXRT, ASCA, Suzaku, InFocus
- Plasma-etched precision silicon combs (Shattenburg et al. 2000): proposed for Con-X
- In-Situ precision machined graphite spacers (Craig et al. 1998): HEFT
- "Actuate and Affix" (Hair et al. 2002; Owens et al. 2006): being studied for Con-X
- Micro-Pore Optics (Beijrsbergen et al. 2004): XEUS optics
- **"Fabricate and Assemble" (Zhang et al. 2006)**

The Whole Process on One Page

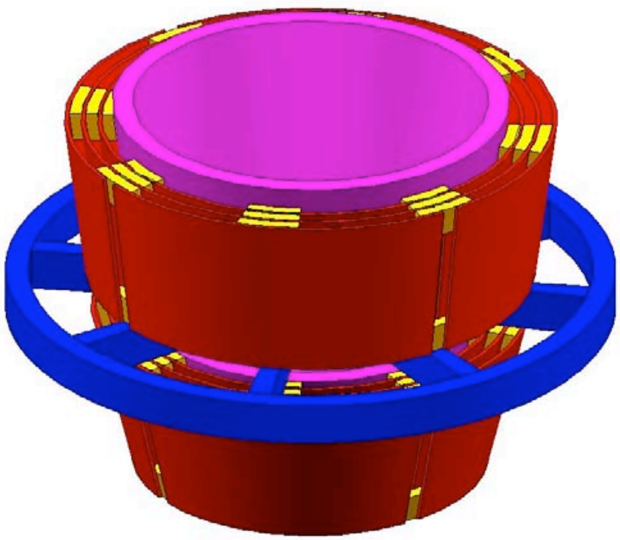


1. Glass sheet
2. Slumping process
3. Wedged sheet
4. Mirror segment
5. Slumped wedged spacer sheet
6. Finished spacers
7. Optical CCD (focus of the primary mirror segments)
8. Optical CCD (focus of the telescope)
9. Wagon wheel (blue)
10. Alignment core (purple)
11. 6-DOF stage
12. Mirror segment cradle/mattress
13. Optical collimator
14. Spindle (not shown)
15. Epoxy and its application and cure (not shown)
16. Precision radius gauge (not shown)

Features of "Fabricate and Assemble"

- **No stack-up error: each mirror segment is integrated with its own specific spacers**
- **Each mirror segment is treated exactly the same as every other mirror: if you can align/integrate one mirror, you can align/integrate all of them**
- **Each component of the entire system is separately fabricated and measured: we cut no "corners"**
- **Each mirror segment is integrated in its "gravity-free" using the support mattress**
- **Each mirror segment is integrated into the assembly stress-free: no surprise at the completion of assembly when any residual stress could cause potentially devastating system level distortions**
- **Each mirror segment performs double duty: (1) serving as an optical element, and (2) serving as part of the mechanical structure**
- **Built-in redundancy to prevent inadvertent mistakes**

Mirror assembly for NeXT



- Focal length: 12m
- ID: 120mm; OD: 450mm
- No. of Shells: 140
- Mirror segment:
  - *200mm in axial length*
  - *90^o in azimuth*
  - *0.3mm thick*
- Total mass: <50kg
  - *Mirror segments: <40kg*
  - *Spacers: <3kg*
  - *Wagon Wheel: <3kg*

Practical Considerations

- **Optical design:** conical approximation, contributing **5** arc-sec HPD
- **Forming mandrels:** either conical or cylindrical with axial figure error contributing less than **8** arc-sec HPD
- **Major error contributors:**
  - Glass forming: **< 20** arc-sec HPD
  - Alignment/integration error: **< 10** arc-sec HPD

Expected mirror assembly performance: 25 arc-sec HPD

Summary

- Directly slumped glass mirrors are close to meeting Con-X requirements. Once ***metrology and mid-frequency problems*** are solved, they should be as good as the mandrels, close to reaching the Con-X goal of 5 arc-sec HPD.
- The "Fabricate and Assemble" is being studied as an integration method for making both large (Con-X) and small (NeXT) assemblies.
- Given schedule and budgetary considerations of a mission like NeXT/MIDEX
  - 30 arc-sec HPD for a NeXT mirror is straightforward and relatively easy to implement
  - 10-20 arc-sec HPD is likely doable, but with care and a little more development
- **We are in the process of making a prototype for X-ray test and for vibration and acoustic tests**